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Spatial and temporal variability of grassland yield and its response to climate change and anthropogenic activities on the Tibetan Plateau from 1988 to 2013

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ABSTRACT

Accurate and periodic assessment of grassland yield (GY) is of great importance for the management of high altitude plateau grasslands. The Tibetan Plateau (TP) is a very important pastoral area that provides a microcosm of typical alpine grassland ecosystems. Based on remote sensing data, meteorological datasets and observational plant biomass data, we used the Global Production Efficiency Model and Soil and Atmosphere Model (GLOPEM-CEVSA) to estimate GY and its response to climate change and anthropogenic activities on the TP from 1988 to 2013. We quantitatively analyzed spatiotemporal dynamic changes of GY for four geomorphological divisions and five main grassland types. For the 26 years of the study, average annual total GY was 515.8 kg/ha/yr and gradually decreased from the southeast to the northwest of the TP. Annual GY fluctuated from year to year but had an overall positive trend (4.2 kg/ha/yr). Spatiotemporal variation of GY was greatly influenced by spatial heterogeneity. For the total area, the proportion showing a significant increase in GY was 45.2%, while only 12.6% showed a significant decrease. For the main grassland types, GY of Alpine Meadow was highest and had the highest slope of increase. The pattern of decrease of GY from the southeast to the northwest was predominantly related to climate gradients. Regional correlation analysis indicated that warming temperature promoted positive increase of GY for almost all the region. Annual precipitation was related to a less significant decreasing trend of GY over all the TP apart from an increase of GY in the middle area of the north. The grazing pressure index decreased over the years by control of livestock numbers, the reduction of grazing pressure assisting restoration of alpine grasslands. However, grazing pressure on the TP in 2013 remained too high and overloaded. Nevertheless, grassland protection and restoration projects have mitigated grassland degradation in some areas, promoted grassland restoration, and increased incomes of herdsmen. The study indicates that continuation of these projects is critical for the restoration and sustainable use of the TP grasslands.

1. Introduction

Grasslands as the largest terrestrial ecosystem in China, cover about 41.7% of country's territory (Department of Animal and Husbandry and Veterinary of Ministry of Agriculture of China, 1996). They provide vital natural resources for human survival and play an important role in ecosystem services. Nevertheless, in recent years, grasslands have suffered from pronounced warming, droughts and extreme climatic events that have changed their phenology (Ni, 2000; Zhang et al., 2013), reduced their primary productivity (Wu et al., 2011; Harrison et al., 2016), and strained their livestock carrying capacity (Deng et al., 2017; Qian et al., 2012). Human activities, particularly overgrazing by

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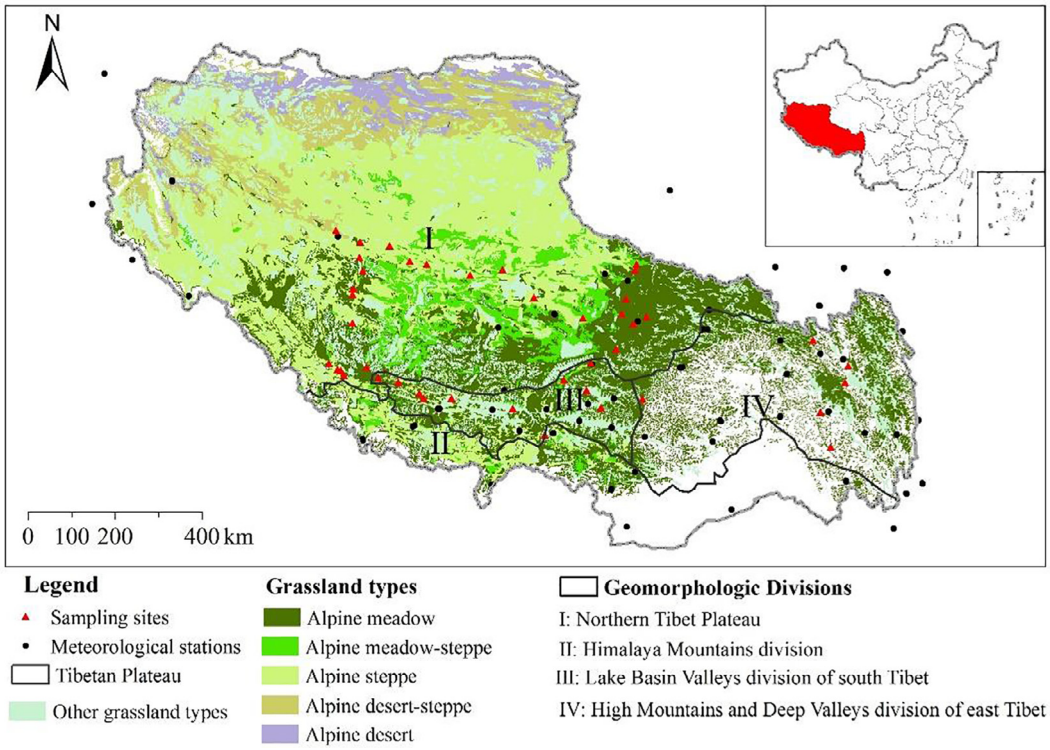

Fig. 1. Spatial distribution of grassland types, geomorphological divisions, meteorological stations and sampling sites on the Tibetan Plateau. (*White areas are not covered by grassland.*)

domestic livestock and clearance for cultivation and urbanization, have had negative effects on grasslands. As a result, grasslands have developed serious problems, including grassland degradation, aggravated soil erosion and water loss, biodiversity reduction and decline of service function (IPCC, 2013). To mitigate these problems and to protect grassland resources, the Chinese government has made considerable effort to implement a series of ecological protection and restoration projects (Lü et al., 2015).

Grassland yield (GY) is a vital measurement index of grassland resource dynamic research and also a key factor in determining forage utilization and balanced animal carrying capacity. However, GY's long-term responses to climate change and anthropogenic activity are not yet fully understood. Grazing pressure is an immediate and dominant source of natural grassland degradation. Achieving balance between grazing animal numbers and forage is beneficial for the protection of grassland ecosystem environments and promoting development of sustainable animal husbandry.

Several studies have concentrated on vegetation activity dynamics by using representative indicators based on remote sensing data through models, such as normalized difference vegetation index (NDVI), fractional vegetation cover (FVC), and net primary productivity (NPP), and have paid particular attention to climatic factors affecting these (Zhang et al., 2013; Zhang et al., 2014). Most of these studies have paid insufficient attention to GY and its response to specific human activities, e.g. livestock grazing and ecological engineering (Mao et al., 2014). Furthermore, they have lacked quantitative description and direct evaluation of the carrying capacity of natural pasture.

The Tibetan Plateau (TP), described as the roof of the world and the water tower of Asia (Immerzeel et al., 2010), supports the world's largest area of typical alpine grassland ecosystems that are particularly vulnerable to climate change and human activities (Piao et al., 2012). Furthermore, functioning of the TP has an important effect on local economic development and ecological security (Sun et al., 2012; Zhang et al., 2015). With fragile and complicated environments, many ecological problems have developed on the TP, including grassland degradation, soil erosion, biodiversity decline, desertification and related economic recession (Chen et al., 2014b; Harris, 2010; Yu et al., 2012). Consequently, the TP provides an ideal area to study the responses of grassland ecosystems to climate change and anthropogenic activities.

Based on an overall consideration of grassland management practices, availability of remote sensing and meteorological data, feasibility of the assessment method, and completeness and consistency of statistical and field data, we chose 1988–2013 as the study period, simulated NPP by using GLOPEM-CEVSA, and calculated GY by reliable formulae. The main objective of this study was to measure the spatial and temporal variability of grassland yield from 1988 to 2013 in relation to climate change and grazing activity on the TP. Also, it took into account the influence of grassland protection and restoration projects on the TP grasslands. Furthermore, we endeavored to investigate mechanisms of grassland changes from the perspective of natural and anthropogenic causes. The study aims to promote sustainable development of China's high-altitude grasslands and to further understanding of the function of the national ecological security shelter plan. Our findings intend to assist ecological monitoring and to provide a reference for grassland ecological protection policy-making and planning.

2. Materials and methods

2.1. Study area

The Tibetan Plateau, surrounded by the Himalaya, Kunlun and Tanggula Mountains, forms the main body of the Qinghai-Tibetan Plateau and has complex and diverse topography and geomorphology. Its area is 1.2×10^6 km^2 (78°15′–99°07′E, 26°50′–36°29′N) and it has a population of more than 3 million people, 80 percent of whom are herdsmen. It has four geomorphological divisions: Northern Tibetan Plateau, Himalaya Mountains division, Lake Basin Valleys division of south Tibet, and High Mountains and Deep Valleys division of east Tibet

(Yang et al., 2014). The Northern Tibetan Plateau, the core of the Tibetan Plateau, has an average altitude above 4500 m and is the main pastoral region of the TP. The High Mountains and Deep Valleys division of east Tibet forms part of the Hengduan Mountains and is composed of a series of high mountains and deep valleys that lie in east-west and south-north directions. The Lake Basin Valleys division of south Tibet is located between the Trans-Himalayan and Himalayan Mountains. The western part of the Himalayan Mountains division has high altitude and a dry and cold climate, whereas its eastern part has a milder climate and abundant rainfall (Fig. 1).

Due to the region's average elevation of higher than 4000 m, the TP has a plateau continental climate with an annual average temperature of −5°C to 5 °C. It is mostly included in the arid and semi-arid area of China with annual precipitation below 500 mm (Zheng et al., 2010). Annual precipitation decreases from 5000 mm in the southeast to 50 mm in the northwest. The entire region has strong solar radiation and long hours of sunshine with average annual sunshine hours varying from 1500–3400 h (Wang et al., 2016). It has the characteristics of dry climate, strong winds, and an annual wind erosion factor index above 50. With nearly half a year or more of cold days and a wind erosion factor index of about 100 in the dry and windy dry season, the TP is one of the areas of China that have strong wind erosion.

The TP has natural grassland covering 8.2×10^6 km^2 that occupies about 80% of its total area and provides more than 25% of the natural grassland area of China. Alpine grassland is the dominant ecosystem, with a vegetation type transition of Alpine Meadow, Alpine Meadow-steppe, Alpine Steppe, Alpine Desert-steppe and Alpine Desert from southeast to northwest (Fig. 1). Its main plant species include *Kobresia pygmaea*, *Kobresia tibetica*, *Kobresia humilis*, *Stipa purpurea* and *Dassiphora fruticose* (Yang et al., 2004). The TP is one of the five traditional pastoral areas of China and has a long history of livestock farming. The main livestock are cattle, buffaloes, sheep and goats.

2.2. Field data

To collect the localized key parameters for the model and to evaluate the simulated GY, we sampled various grassland types at 45 representative grassland field sites on the TP during the annual peak growing periods (in August and September) from 2004 to 2011. For each field plot, we recorded geographic coordinates, altitude, soil condition, grassland type, vegetation cover, and the proportion of cover provided by the dominant plant species. The above-ground biomass (including live biomass as well as standing dead biomass produced in the current year) was randomly harvested from 1 m × 1 m quadrats with five replicates at each site. For alpine meadow sites 0.5 m × 0.5 m quadrats were used (Hu et al., 2010; Zhou et al., 2016). Sampled biomass was weighed after 48 h of drying in an oven set at 65 °C and standardized as dry matter (DM)/m^2. Below-ground biomass was mostly sampled in 10 cm depth layers to 30 cm within each quadrat. Roots and other below-ground biomass were separated from soil by washing with water through a 0.3-mm-mesh sieve. To minimize influences of human disturbance, sample sites were fenced and not grazed or cut in the sampling year. Sampled data, based on their spatial distribution, were divided into two parts: 75% were used to calibrate the parameters of the modeling analysis and 25% were used to validate the feasibility of the model.

2.3. Climate data

Climate data were collected from 53 meteorological stations of the China Meteorological Administration (CMA) and the National Climatic Data Center (NCDC) across the TP during the period 1975–2013 (Fig. 1). The spatial data of temperature, precipitation, relative humidity, wind speed, and sunlight hours for the TP were interpolated into 1 km resolution by using ANUSPLIN version 4.2. To improve the accuracy of the interpolation, we put the Digital Elevation Model (DEM) data as a covariate in the ANUSPLIN. DEM data was from the 90 m SRTM (SRTM3 V4.1) (Shuttle Radar Topography Mission) images (http://srtm.csi.cgiar.org/) and was resampled to 1 km for this study.

2.4. Grassland yield calculation

Grassland yield (GY) of the TP for different grasslands during 1988–2013 was calculated from NPP with 1 km resolution. To increase the accuracy of spatial and temporal estimation of grassland ecosystem NPP, we used the integrated GLOPEM-CEVSA model. On the basis of taking into full account the changes of the whole growing seasons of the grasslands and the reliability of data on the TP, we adopted the satellite-derived fraction of photosynthetically active radiation absorbed by vegetation (FPAR) and relevant climate data with a spatial resolution of 1 km and a temporal scale of 8 days (Wang et al., 2017).

GY was estimated from procedures defined by Gill et al. (2002) and Fan et al. (2010). We used the ratio of living belowground biomass to total belowground biomass of 0.79 as determined by field measurements made by Zhou (2001). The distribution and areas of the grassland types were determined from the 1:1,000,000 scale Chinese grassland resources map (ECAGRC, 1993). GY estimates were determined as kg dry matter (DM)/ha.

2.5. Grazing pressure index calculation

Grazing by domestic livestock is recognized as a major ecological factor in grasslands and has extensive and profound effects on grassland productivity (Noy-Meir et al., 1989; Vandegehuchte et al., 2017). We used the grazing pressure index (IP), defined as the ratio of actual and theoretical optimum carrying capacities (Fan et al., 2010), to evaluate the effects of grazing on grassland productivity on the TP from 1988 to 2013. If IP = 1, the carrying capacity is at the optimum state; if IP > 1, the number of livestock exceeds the optimum state, whereas for IP < 1, the grassland has the capacity to carry more livestock. The numbers of livestock for each county were obtained from statistical data provided by the National Bureau of Statistics of China (Tibet Autonomous Region Bureau of Statistics, 2014). Small livestock (sheep and goats) were regarded as equivalent to standardized sheep units (SUs), and large animals (horses and cattle) were regarded as four SUs (Chen et al., 2014a).

IP was calculated as:

$$IP = C_s/C_l \quad (1)$$

where C_s is the actual carrying capacity (SUs/ha) and C_l is the recommended sustainable carrying capacity (SUs/ha). C_s and C_l was calculated from Eqs. (2) and (3):

$$C_s = (C_n*(1 + C_h)*G_t)/(A_r*365) \quad (2)$$

where C_n is the number of livestock (SUs) at the end of the year. C_h is the livestock slaughter rate (%). In this study, C_h was set to 30% according to local statistical data. A_r is the natural grassland area (ha). According to the actual situation of the TP, G_t is the grazing period (days), which was set to 365 days during 1988–2013.

$$C_l = (Y_m*U_t*C_O*H_a)/(S_f*D_f*G_t) \quad (3)$$

where Y_m is the grassland yield (kg/ha); U_t is the utilization percentage of herbage (%); C_O is the proportion of the area available for pasture (%); H_a is the rate of the edible herbage (%); S_f is the daily intake fresh forage of one sheep unit (kg/SU/d); and D_f is the dry weight of fresh herbage (%). Based on consideration of the actual situation of grasslands on the TP, through consultation with local experts and with reference to relevant literature (Qian et al., 2007; Yang and Yang, 2000), the values for U_t, C_o, H_a, S_f, and D_f were set to 70%, 92%, 80%, 4 kg/SU/d, and 33%, respectively.

2.6. Data analyses

The temporal and spatial change characteristics of GY were detected using spatial statistical analysis and mapping with ArcGIS 10.3. Regression analysis was applied to analyze the long-term trends of GY, climatic factors and IP. Pearson's correlation analysis was applied to investigate the relationships and their significance between GY and climatic factors. To identify abnormal trends of livestock numbers on the TP, we applied the piecewise regression model to quantitatively identify the turning point from 1988 to 2013 (Toms and Lesperance, 2003). The FVC was calculated by the dimidiate pixel model (Ivits et al., 2013). The numerical analysis and statistical computing was done using R software, and correlation analysis used python programming languages in the ArcGIS platform.

To synthetically reflect the conditions of grassland change, we determined FVC indices, which can be used as indicators of the quantitative characteristics of vegetation and an evaluation index of grassland degradation, salinization and desertification (Mu et al., 2013). For quantitative analysis of the achievement of the government grassland protection and restoration projects on the TP, we compared FVC, GY and IP before and after implementation of the projects.

3. Results

3.1. Spatial and temporal changes of grassland yield

The correlation between the field measurements of grassland yield of 45 sites and predicted grassland yield (GY) was highly significant (Fig. 2).

The simulated results show that the annual grassland yield averaged over all TP from 1988 to 2013 was 515.8 kg/ha (Fig. 3a). Within the spatial distribution, GY on the TP showed a gradual decrease from southeast to northwest (Fig. 3b). As examples, the highest average GY was above 1000 kg/ha in the High Mountains and Deep Valleys division of east Tibet, GY ranged from 400–800 kg/ha in central regions, and the lowest GY was < 100 kg/ha in the northwest (Fig. 3b).

Over the 26 years, annual GY of the entire TP had a fluctuating but progressive increase of 4.2 kg/ha/yr. To consider temporal and spatial changes together, the slopes of the changes of GY over years and significance testing of GY are plotted in Fig. 4. The proportion showing a significant increase in GY was 45.2% of the total area, with a distribution mainly in the mid-east and north of the TP. By contrast, 12.6% of the grassland area showed a negative change in GY, and this occurred mostly in the southeast and western margin of the TP.

For GY trends of the different geomorphological divisions, the decrease of GY in the High Mountains and Deep Valleys division of east Tibet was not significant and had relatively higher year to year variation than for the other divisions. GY in the eastern part of the Lake Basin Valleys division of south Tibet had an obvious decreasing tendency whereas GY in the western region significantly increased. There were no remarkable changes in GY distribution for the Northern Tibetan Plateau (Table 1).

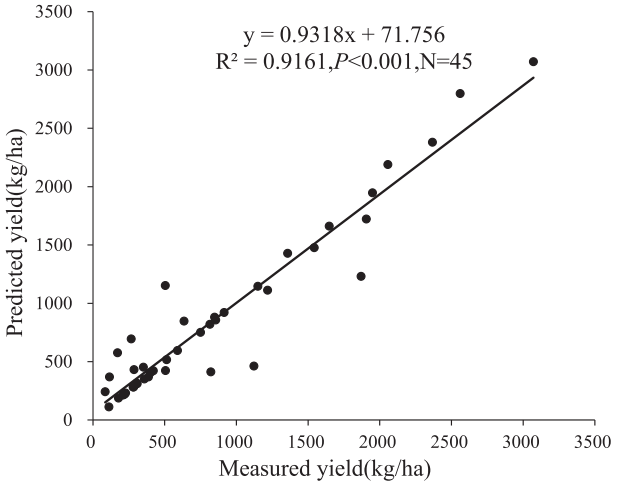

Fig. 2. The relationship between measured grassland yield of 45 sites on the Tibetan Plateau and predicted grassland yield.

There were significant differences of GY amongst the grassland types. The total area of Alpine meadow, Alpine steppe, Alpine desert-steppe, Alpine meadow-steppe and Alpine desert accounted for approximately 95% of the area of natural grassland on the TP. Means and slopes of change of GY of the grassland types over the 26 years of the study are shown in Table 2 and Fig. 5.

Alpine meadow had the highest GY and slope of increase and Alpine desert the lowest. Alpine desert-steppe had the highest CV and Alpine meadow the lowest. The slopes of change of GY were significant for all grassland types except for Alpine desert-steppe.

3.2. Climate changes

During 1975–2013, mean annual temperature (MAT) on the TP was −0.73 °C, with an overall trend of higher temperature in the southeast and lower temperature in the northwest. The MAT increase of above 2 °C in Lake Basin Valleys division of south Tibet was the highest, while that in Northern Tibetan Plateau showed a decrease of below 0 °C (Fig. 6a, c, e). Its mean annual precipitation (MAP) during 1975–2013 was 449.8 mm. Precipitation had a similar distribution pattern as temperature, with mean MAP of the southeast region above 600 mm and that of the west and north region below 200 mm (Fig. 6b, d, f). Over nearly 40 years, MAT showed a significant positive trend (0.53 °C per decade, $P < 0.001$) across the TP, while no significant increases were observed in MAP (9.17 mm per decade, $P = 0.171$). The TP had a higher warming trend from 1988 to 2013 (0.6 °C per decade, $P < 0.001$) than from 1975 to 1987 (0.26 °C per decade, $P = 0.355$), while MAP had a different trend for the period 1975–1987 (72.94 mm per decade, $P = 0.073$) than for the period 1988–2013 (−3.37 mm per decade, $P = 0.764$) (Fig. 7).

During 1988–2013, changes of the trends of temperature and precipitation had high levels of variation in spatial heterogeneity. The strongest warming trend occurred in the Northern Tibetan Plateau and particularly in the north of that division. Because they were mainly covered by forest and water bodies, the rates of temperature rose in the High Mountains and Deep Valleys division of east Tibet and the Lake Basin Valleys division of south Tibet were relatively slow. MAP averaged for Northern Tibetan Plateau showed a trend of increase from 1988 to 2013 of 0.46 mm/yr. Other divisions of the TP showed a reducing trend of MAP. Since 2000, except for the climate of the High Mountains and Deep Valleys division of east Tibet becoming warmer and drier, most of the TP has become warmer and wetter.

3.3. Correlation of grassland yield with climatic factors

For the whole study area, GY was positively correlated with long term changes of MAT ($r = 0.79$, $P < 0.01$). The correlation between GY and MAP ($r = -0.09$, $P > 0.05$) was not significant. In regard to spatial distribution, GY showed a gradual decrease from southeast to northwest of the TP that corresponded with gradients in temperature and precipitation. GY increased in the warmer and wetter climate of the southeast and was limited by the colder and drier climate of the northwest (Fig. 8).

There are complex terrain and vegetation diversity patterns on the TP. Thus, we calculated the correlations for different grassland types between GY and MAT and MAP from 1988 to 2013. For the five main grassland types, positive correlations between GY and MAT were significant for four of the types, but the correlation of only one grassland type between GY and MAT wasn't significant (Table 3). For MAT,

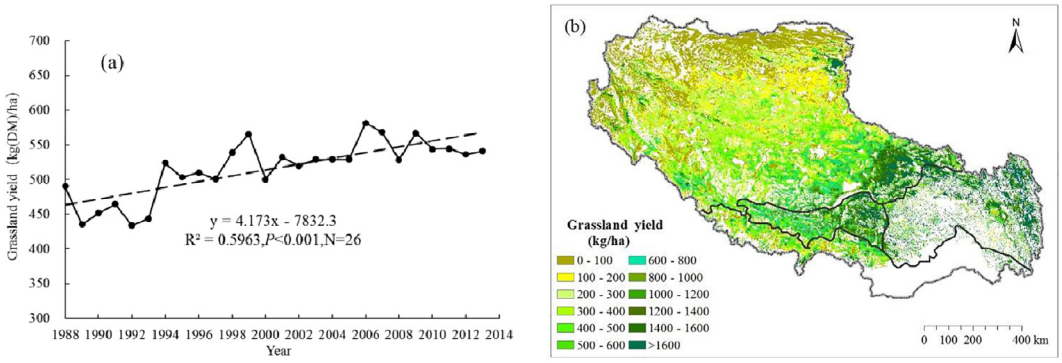

Fig. 3. (a) Fluctuations and progressive change of annual grassland yield (GY) and (b) spatial distribution of average annual grassland yield (GY) on the Tibetan Plateau from 1988 to 2013. *(White areas are not covered by grassland.)*

Alpine meadow had the strongest correlation, those for Alpine meadow-steppe and Alpine desert were of intermediate strength, that of Alpine steppe was of lowest significance, and that for Alpine desert was not significant. Only Alpine steppe had a significant correlation between GY and MAP (Table 3).

3.4. Grazing pressure assessment

From 1988 to 2013, the inter-annual mean livestock number on the TP was 4120×10^5 SUs/yr. Over the 26 years, livestock number increased with a slope of 11.2×10^5 SUs/yr for the whole area ($P < 0.001$), but it showed different trends in the periods 1988–2005 and 2006–2013 (Fig. 9). From 1988 to 2005, livestock number increased at a slow rate of about 16.5×10^5 SUs/ yr. From 2006 to 2013, livestock number plummeted at a rate of 90.1×10^5 SUs/yr, with a significant total decrease of 14.6% ($P < 0.001$).

The average grazing pressure index (IP) on the TP from 1988 to 2013 was 1.63, indicating that the grassland was overloaded by 63%. IP decreased gradually from 1988 to 2013, with a slope −0.9%/yr ($P < 0.01$). Over the 26 years, the highest and lowest values of average annual IP were 1.9 in 1992 and 1.4 in 2013, respectively (Fig. 10a). The spatial distribution of IP from 1988 to 2013 showed that IP overloading exhibited considerable variation over the TP and was generally above one in the east, and particularly in the mid-southeast TP (Fig. 10b).

3.5. Changes in key indicators caused by protection and restoration projects

Since 2004 a series of projects was launched by the government to prevent grassland degradation by protecting and restoring grasslands. The annual mean FVC and GY during the project period 2005–2013 were 22.3% and 548.8 kg/ha, respectively, which were higher than 20.6% and 498.3 kg/ha before implementation of the projects (1988–2004) (Fig. 11a, b). The annual mean IP during the projects period was 1.6 and declined by 7.2% from that before implementation of the projects (1988–2004) (Fig. 11c). After implementation of the projects, annual FVC and GY increased significantly and IP fell markedly.

4. Discussion

4.1. Effects of climate change on grassland yield

Climate is an important biophysical factor influencing vegetation growth. Temperature and precipitation are important factors influencing vegetation inter-annual variations (Keeling et al., 1996). Previous research has shown that climate change dominated grassland productivity changes in most parts of the Qinghai-Tibet Plateau, accounting for 79.6% from 1982 to 2001 and 56.6% from 2001 to 2011 of the driving forces of grassland ecosystem change (Chen et al., 2014a).

Rising temperatures and fluctuating precipitation jointly influenced inter-annual variations of GY on the TP from 1988 to 2013. GY changes were positively associated with MAT on most of the TP for many of the years, while GY troughs corresponded to precipitation variation between adjacent years only on some parts of the Northern Tibetan Plateau (Fig. 8 and Table 3). It could be concluded that the dominant and most direct climatic factor determining GY variability of the whole TP was temperature. However, given that precipitation in the arid and semi-arid areas of the TP was a dominant factor determining grassland growth (Zeng and Yang, 2008), we conclude that precipitation was also an important limiting factor determining variation of regional distribution of growth and productivity of grasslands on the TP.

During 1988–2013, GY change on different areas of the TP was closely correlated with climate change (Fig. 8). Rising temperatures were conducive to increase of GY in the most parts of the study area.

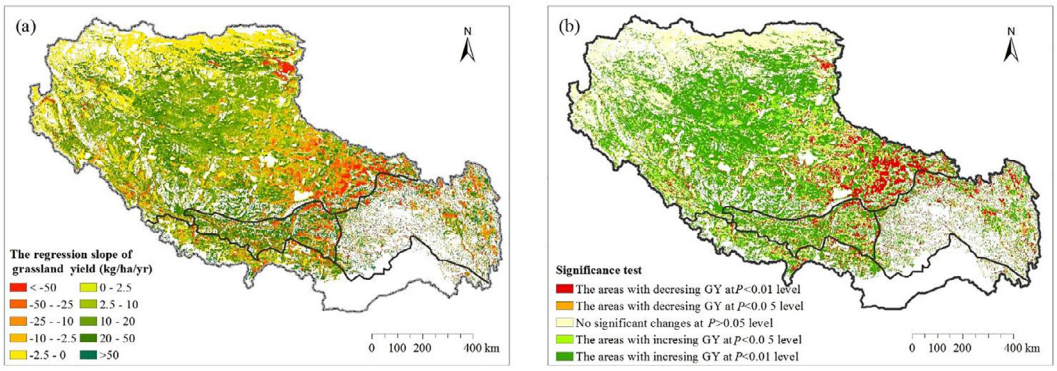

Fig. 4. (a) Spatial pattern of the slope of the regression of changes of average annual grassland yield (GY) and (b) significance test of this data during the period 1988–2013 on the Tibetan Plateau. (*White areas are not covered by grassland.*)

Table 1
Assessment of grassland yield (GY) functions for geomorphological divisions of the Tibetan Plateau during 1988–2013.

Geomorphological divisions	Mean GY	Standard deviation of GY	CV (%) of GY (kg/ha/yr)	Slope of regression of GY change/yr	Significance of regression slope (*P*)
Northern Tibetan Plateau	365.12	47.22	12.93	4.90	< 0.001
Himalaya Mountains division	502.67	65.34	13.00	5.69	< 0.001
Lake Basin Valleys division of south Tibet	954.90	107.02	11.21	7.59	0.004
High Mountains and Deep Valleys division of east Tibet	1350.57	108.27	8.02	−3.40	0.237

Table 2
Grassland yield (GY) functions of grassland vegetation types on the Tibetan Plateau from 1988 to 2013.

Grassland types	Percentage (%)	Mean GY (kg/ha/yr)	Standard deviation of GY	CV (%) of GY	Slope of regression of GY change/yr	Significance of regression slope (*P*)
Alpine meadow	38.62	896.35	70.75	7.89	5.47	< 0.001
Alpine meadow-steppe	8.10	343.97	37.72	10.97	3.15	< 0.001
Alpine steppe	38.62	304.00	55.17	18.15	4.00	0.003
Alpine desert-steppe	11.04	223.45	75.86	33.95	3.14	0.116
Alpine desert	5.65	141.46	34.91	24.68	1.75	0.053

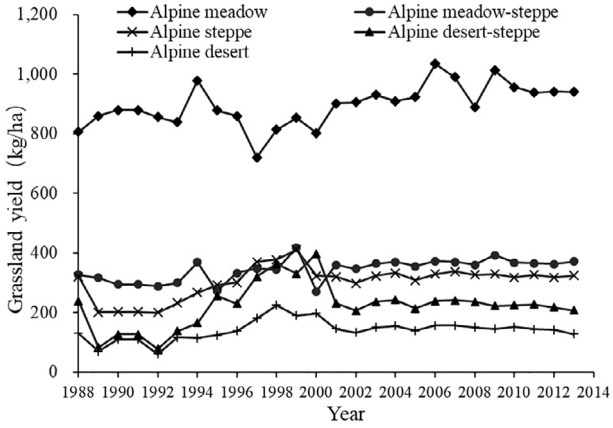

Fig. 5. Changes of grassland yield (GY) of the main grassland types on the Tibetan Plateau from 1988 to 2013.

However, over 26 years, climate warming accelerated the extent of drought damage in some southeastern areas of the Northern Tibetan Plateau and during the same time precipitation decreased in the same region. Further, warming and drying of the climate in some northwest areas of the TP was related to decline of GY (Fig. 8). Precipitation and GY in central areas of the Northern Tibetan Plateau were strongly positively related. GY in most of the central areas showed an obvious increasing tendency arising from the trend towards a warmer and wetter climate (Fig. 4). As temperature rose and precipitation reduced, water availability for plant growth on the southeast Tibetan Plateau may be declining and so this may lead to reduction of GY in certain areas. Other studies have also shown that temperature has had a positive effect on GY in the west of the TP, whereas it has had a strong negative effect on GY on the central and southern parts of the Plateau (Gao et al., 2016).

Especially sensitive to climate change, particularly global warming, are the high altitude and cold alpine ecosystems and the large-area of glaciers and snow on the TP. The active phenological period on the TP has been lengthened due to climate warming, advancing re-greening, heading and flowering of forages and delaying the yellowing and withering of plants (Zhao et al, 2016). In regard to the phenological phases of grassland vegetation, rising temperature, especially by increasing the length of the growth period, has promoted increase of GY on the TP. Making effective use of climatic data from weather stations close to grazed areas is important for guiding use by herdsmen of the forage produced in these areas.

Rising temperatures can lead to the melting of glaciers, snow and permafrost. This could influence and intensify degeneration of the grasslands of the Northern Tibetan Plateau as a consequence of freezing and thawing erosion. With acceleration of climate warming related to anthropogenic greenhouse gas emissions, glaciers and snow on Mount Everest are melting more rapidly and permafrost is thawing (Chen et al., 2013). Release of water from ice may promote the growth of grassland vegetation and enhance GY. Warming-induced permafrost thawing and glacier melting will probably make the ecological environment even more fragile and degraded. Furthermore, a warmer and drier climate combined with overgrazing could change the physical and biological characteristics of previously frozen soil to further accelerate detrimental changes of TP alpine grassland ecosystems (Meng et al., 2014).

4.2. Effects of grazing activity on grassland yield

Grazing is the dominant form of grassland use in arid and semi-arid biomes, and the number and type of livestock directly affect grazing intensity (Wen et al., 2013; Ren et al., 2016). Grazing directly influences GY change, and the balance between forage supply and animal numbers mainly depends on grazing intensity and management (Cao et al., 2004). Overgrazing can cause degradation and desertification of natural grasslands, even “Black Soil Beach”, which has bare land in winter and sparsely covered land with weedy forbs or poisonous plants in summer (Su et al., 2014). Thus, it is both necessary and highly critical to evaluate and implement appropriate livestock carrying capacity for alpine grassland ecosystems and to adjust the number of livestock reared.

Livestock are essential for the livelihood of local herdsmen and rearing more livestock can give them increased economic returns. Since the early 1980s, the Chinese government has implemented several major land use policies and grassland development strategies to promote animal husbandry on the TP. These include the Nomad Settlement Project, the Household Production Responsibility of Grasslands, Husbandry Cooperativization, and provision of supplementary feeding.

Comparing the spatial pattern of the slope of the regression of change of average annual GY (Fig. 4) and the spatial distribution of average annual IP (Fig. 10b), significant decreases of GY were more likely to be coincident with high values of IP in the region. In the southeast of Northern Tibetan Plateau, where IP was above 1.5 with a range of IP of 1.5–5, GY decreased markedly. By contrast, in the central regions of Northern Tibetan Plateau, IP was less than one and hence not

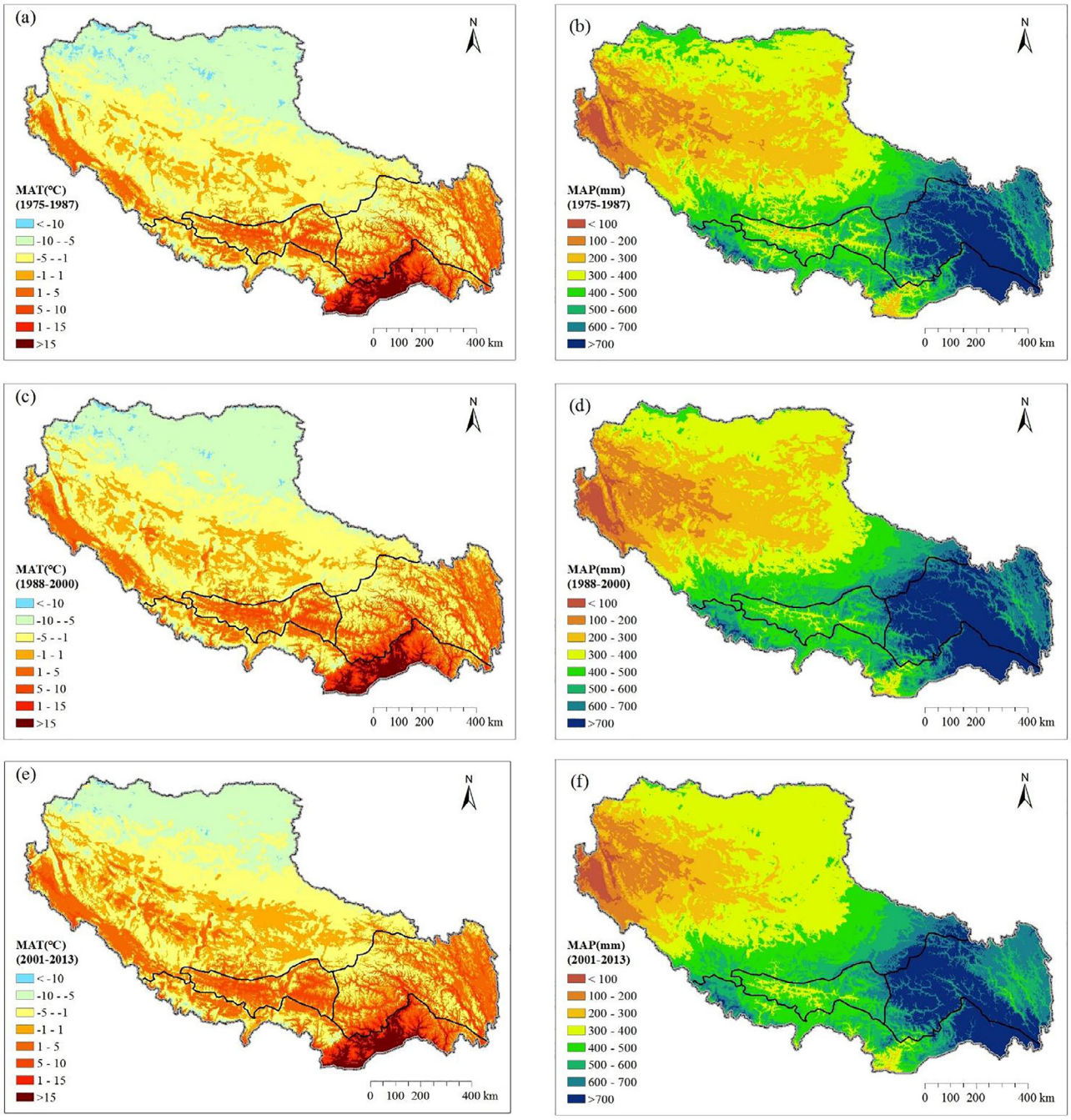

Fig. 6. Spatial distributions of mean annual temperature (MAT) and mean annual precipitation (MAP) changes on the Tibetan Plateau for the periods 1975–1987, 1988–2000 and 2001–2013.

overloaded, and GY showed a significant increase. In the northwest, IP was below 0.5 and largely remained unchanged, and GY also remained unchanged. Generally, GY on the TP had an overall positive trend from 1988 to 2013 benefitting from livestock number controls and reduced grazing pressure.

Although GY on the TP from 1988 to 2013 increased slightly, herbage supply still could not meet the demand of livestock consumption requirements. Particularly, when GY on the TP showed little change from 2000 to 2005, livestock numbers increased steeply (Figs. 3, 9 and 10a). Thus, marked imbalance between grassland supply and livestock demand occurred. Consequently, for a period grassland overloading became more serious. If this overloading had continued, further grassland degradation would have resulted in decline of ecosystem services and disrupted ecological balance. However, from 2006 the number of livestock markedly decreased and IP showed an overall decline to 2013 (Figs. 3, 9 and 10a). The reduced livestock numbers subsequently led to decreased herbage consumption allowing some recovery of the TP alpine grasslands.

Practical livestock production should consider both serious damage to grasslands caused by too high stocking rates and balance this against wastage of GY by under-stocking. Several field-based observational and experimental studies have shown that overgrazing with increased grazing pressure threatened vegetation cover and posed substantial challenges for grassland productivity. Overgrazing has even resulted in desertification in arid and semi-arid grassland ecosystems, such as those in Inner Mongolia and Qinghai Provinces of China and in Timahdit in the Middle Atlas Mountains, Morocco (Deng et al., 2017; Lin et al., 2010; Kéfi et al., 2007). Other studies have shown that controlling

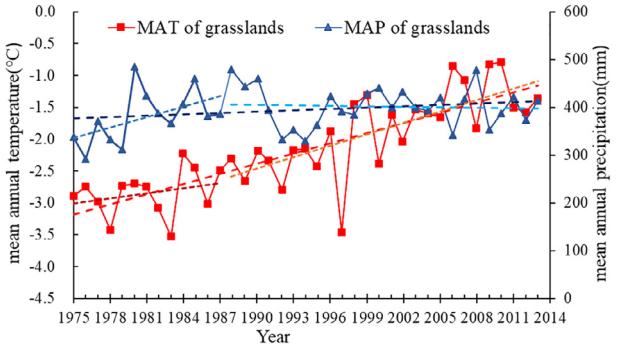

Fig. 7. Inter-annual variations of temperature and precipitation of grasslands on the Tibetan Plateau from 1975 to 2013.

stocking rates can improve degraded grasslands (Liu et al., 2017; Tian et al. 2015; Zhang et al., 2017). Thus, it is necessary to determine livestock numbers and structures based on the carrying capacity of grasslands in order to balance stocking rate with forage supply.

4.3. Achievements of grassland protection and restoration projects

The Chinese government has made proposals to realize balanced sustainable development of the alpine grasslands of the TP (Tian et al., 2015). Grassland protection and restoration projects include the Returning Rangeland to Grassland (RRG) program, the Protection and Construction of the National Ecological Security Shelter Zone (PCNESSZ), and the Ecological Subsidy and Award System (ESAS). Their effectiveness results from restoration measures implemented by local eco-environmental and socioeconomic systems (Chen and Cao, 2013). These projects have used the two main approaches of combatting grassland degradation of reducing grazing pressure on natural grasslands and facilitating grassland recovery from degraded situations. These grassland management practices have improved vegetation cover and increased grassland yield.

The implementation of the RRG program on the TP began in 2004. The program focused mostly on arresting the deterioration of the natural grassland ecosystems and promoting grassland vegetation recovery of alpine grasslands. It was implemented in 25 counties and involved more than 80% of the TP (Zhang et al., 2016). From 2004 to 2013, the government spent approximately 2.9 billion yuan on this program. A total area of 6.4×10^4 km^2 grasslands were fenced and artificial grasslands were established on 1.9×10^4 km^2.

On implementation of the RRG program, local governments gradually reduced livestock numbers especially where stocking rates clearly exceeded grazing capacity. Consequently, livestock numbers markedly decreased from 2006 (Fig. 8). By using fenced areas, effective grazing management measures, chiefly grazing prohibition, rotation or rest, were applied to begin restoration of degraded rangelands. Establishment of sown pastures also reduced the shortage of spring and winter forage in alpine pastoral regions improving the survival and growth of livestock during these seasons. By implementation of the RRG program, grassland degradation and desertification has been brought under effective control and the ecological environments of the TP grasslands have become more stable.

The PCNESSZ was implemented on the TP in 2009 with the aim of reducing the negative effects of global warming and realizing harmony between the stability of ecological environments and the effects of socio-economic development. This program emphasized implementation of protection and improvement of natural grasslands, protection of

Table 3
Correlations between grassland yield (GY) of different grassland types and mean annual temperature (MAT) and mean annual precipitation (MAP) on the Tibetan Plateau from 1988 to 2013.

Grassland types	MAT		MAP	
	R	*P*	r	*P*
Alpine meadow	0.730	**	−0.187	
Alpine meadow-steppe	0.503	**	0.325	
Alpine steppe	0.298	**	0.494	*
Alpine desert-steppe	0.214		−0.068	
Alpine desert	0.409	*	−0.110	
All Tibetan Plateau	0.787	**	−0.086	

* Correlation significant at the 0.05 level (2-tailed).
** Correlation significant at the 0.01 level (2-tailed).

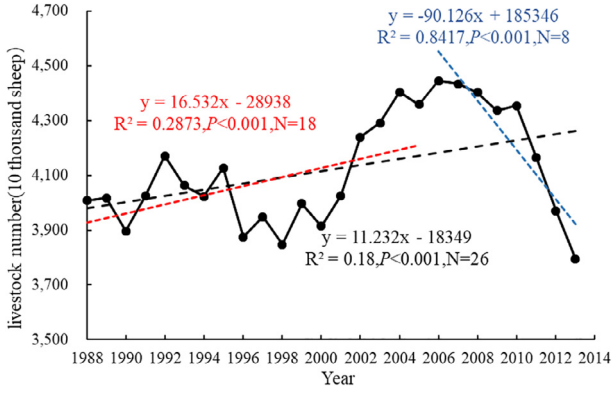

Fig. 9. Time series of total livestock number changes on the Tibetan Plateau from 1988 to 2013 for the periods 1988–2013, 1988–2005 and 2006–2013. *Note: the total number of livestock is the sum of sheep, goats, cattle and horses changed to standardized sheep units (SUs).*

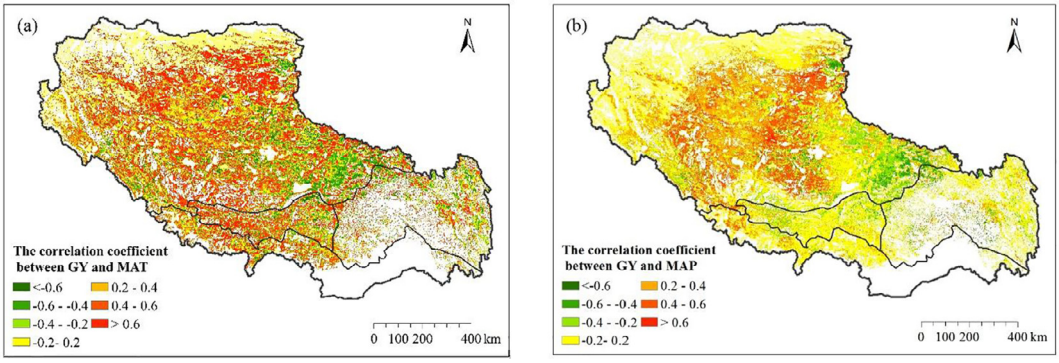

Fig. 8. Spatial distribution of correlations between the grassland yield and climatic factors on the Tibetan Plateau from 1988 to 2013. (a) Correlations of grassland yield (GY) and mean annual temperature (MAT). (b) Correlations of grassland yield (GY) and mean annual precipitation (MAP). *(White areas are not covered by grassland.)*

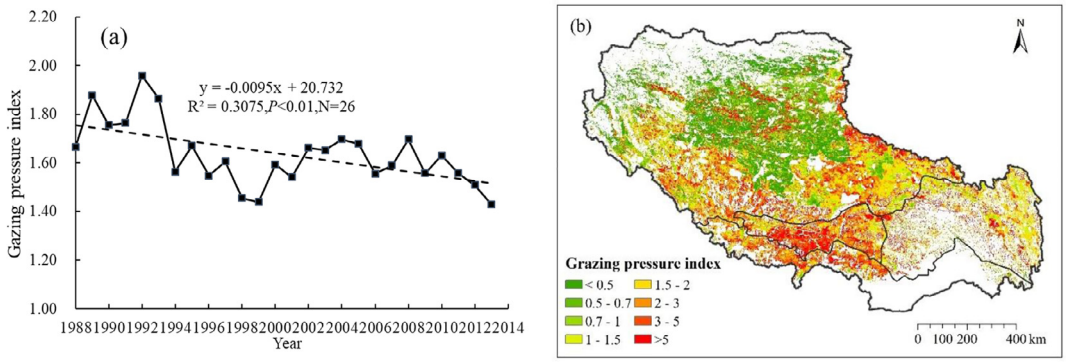

Fig. 10. (a) Changes and (b) spatial distribution of the average annual grazing pressure index (IP) on the Tibetan Plateau from 1988 to 2013 *(There are no data to calculate IP for the white areas.)*

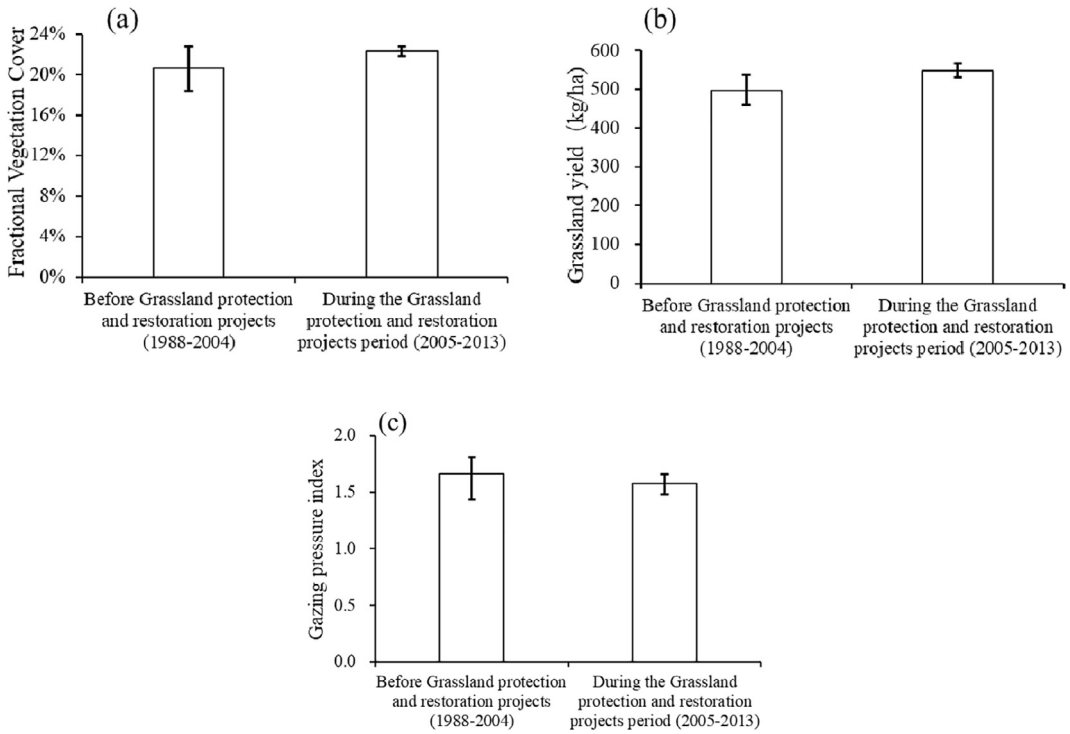
(a)
Fractional Vegetation Cover
Before Grassland protection and restoration projects (1988-2004)
During the Grassland protection and restoration projects period (2005-2013)
(b)
Grassland yield (kg/ha)
Before Grassland protection and restoration projects (1988-2004)
During the Grassland protection and restoration projects period (2005-2013)
(c)
Gazing pressure index
Before Grassland protection and restoration projects (1988-2004)
During the Grassland protection and restoration projects period (2005-2013)

Fig. 11. Comparisons of (a) Fractional Vegetation Cover (FVC), (b) Grassland Yield (GY), and (c) Grazing Pressure Index (IP) before and after implementation of grassland protection and restoration projects on the Tibetan Plateau.

important wetlands, establishment of sown pastures, integrated management of insect pests and rodents, and prevention and control of sand erosion. These measures have greatly improved and stabilized grassland yield. To reverse the loss of the natural grassland resource and deterioration of its ecological environment, by 2014 47 nature reserves of different types had been established in Tibet (nine national-level and 14 autonomous (provincial) reserves). These reserves have a total area of 4.1×10^5 km^2 covering 34.4% of the TP.

The ESAS began on the TP in 2011 with the aims of mitigating the rate of overgrazing, increasing the income of herdsmen, and achieving sustainable development of ecological, economic and social values for Tibet. Based on productivity, the importance of seasonal grazing, ecological services value, and the ecological environmental sensitivity of each alpine rangeland subtype, the Chinese government mainly subsidize the cessation of grazing of grasslands that have particularly harsh environments and which are severely degraded. The ESAS has an innovative approach to control grassland degradation by compensating herdsmen in return for securing rangeland ecosystem conservation and restoring degraded alpine grassland. Reward-compensation provides 14–16% of the gross income of herdsmen. Much of the livestock number decline from 4354.3×10^5 SUs in 2010 to 3795.3×10^5 SUs in 2013 (Fig. 9) may be attributed to the ESAS. In 2013 the per-capita net income of herdsmen in Tibet reached 6578 yuan, which was 3.5 times their 2004 income and 4.9 times that in 2000.

It is appropriate to consider whether the grassland protection and restoration measures implemented were effective because they reduced removal and damage to the biomass, modified botanical composition of the grasslands or affected their physical environments, i.e., soil properties; or because they were conducive to vegetation growth and consequent GY as expounded by Noy-Meir et al., 1989; or because they were due to the combination of a set of these factors. It's beyond the scope of our study to address these broad considerations and consequently we limit it to postulated relationships of GY with standing herbage biomass. Changes in FVC, GY and IP before and after the implementation of grassland protection and restoration projects (Fig. 11) support the conclusion that these projects steadily increased grassland productivity and improved grassland ecosystem health by reducing livestock pressure. Thus, we conclude that these projects have facilitated

forage and animal balance and demonstrate the advantages of sustainable development of animal husbandry.

Wang et al. (2016) concluded that human activity was the dominant factor influencing grassland restoration undertaken for 39.5% of the total grassland area of the Qinghai-Tibet Plateau. Xu et al. (2011) concluded that banning grazing for 5 years maintained higher species diversity and significantly increased the productivity of alpine meadow on the Northern Tibetan Plateau. Su et al. (2014) found that fencing of alpine grassland in Tibet resulted in a significant improvement of grassland condition. Compared with areas not protected by the restoration projects implemented by the Chinese government, FVC, vegetation height and grass yields in ecological project areas were higher on average by 11%, 35.1% and 57.2%, respectively (Liu, 2014). Grassland restoration projects implemented in other countries, e.g., Germany and Canada, have attempted to re-establish native vegetation of degraded grasslands (Conrad and Tischew, 2011; McLachlan and Knispel, 2005). Ecological projects have the potential to remarkably improve recovery of grassland vegetation (Jiang and Zhang, 2016; Shao et al. 2017). Thus, grassland protection and restoration projects have mitigated and even reversed grassland degradation in some areas, promoted forage and animal balance, and achieved sustainable grassland development.

4.4. Uncertainties and future work

We integrated a variety of data, made more field observations, and localized model parameters to increase the accuracy of simulation. However, there are many uncertainties in the mechanisms of natural and human-driven changes of grassland ecosystems. In considering the responses of grassland ecosystems to climate change, many of the biogeographic and geochemical processes involved are largely unknown. This leaves uncertainties in the simulation results obtained from ecosystem models. Due to poor satellite data quality and insufficient field data, we restricted our analysis to calculation of annual GY. In future, we can progressively estimate GY at monthly and even shorter time scales. Further, potential lag effects of climate change for different periods should be taken into account in calculating GY. Also, enforcement points of ecological projects were difficult to locate. As well, the respective contributions of climate change and human activities on GY should be more accurately separated in future studies.

5. Conclusions

The gradual increase of GY of the TP from 1988 to 2013 indicates that the overall condition of the region's grasslands has improved. The significant increase of GY from 1988 to 2013 in the central region could be attributed to a combination of increasing precipitation and temperature and reduced grazing pressure. Reduced GY in the west of the TP may be attributed to increased aridity resulting from climate warming increasing evapotranspiration. Apart from Alpine desert-steppe, the main grassland types, especially Alpine meadow, showed a remarkable increase of GY over the 26 years. Mainly because of continuing high grazing pressure, GY in the central and eastern regions decreased further. Also, areas and grassland types with higher GY showed more substantial changes and seemed to be more reactive to anthropogenic activities.

Managing balance between forage production and livestock requirements is the premise on which to realize grassland protection and sustainable development of grassland husbandry. Although controlling livestock numbers to decrease grazing pressure had been effective in aiding the recovery of grassland ecosystem function, grazing pressure on the TP in 2013 was still too high with an average IP value of 1.4. IP at this level would not allow full restoration of grassland ecosystems and may even cause their further degradation. While ecological restoration implementation, mainly fencing degrading grassland and reducing livestock number, has played a key role in restoring the TP grasslands, the government should continue to apply the strictest protection policy to heavily degraded grasslands and to guide herdsmen to optimize livestock carrying capacity.

Key concerns for the TP are further climate warming caused by factors operating outside the region and the particular vulnerability of its fragile ecosystems to warming (Zhang et al., 2015). Further warming and drying climate change and continued overgrazing will continue to aggravate grassland degradation. Given the history of long-term ecological projects, it is particularly important to carefully choose the appropriate vegetation types for restoration according to local climatic restraints and the particular situations where the best ecosystem services can be established.

The findings of our study have important indications for implementation of restoration projects on the TP in regard to grazing management and determination of livestock numbers that can be sustained on alpine grassland ecosystems. In having considered the effect of climate change on forage production on the TP for the study period, we must also consider the capacity of vulnerable grasslands to adapt to future climate change.

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